A New Air Pollution Model For Edmonton: Part 1

RMD Report 82/14

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A NEW AIR POLLUTION MODEL FOR EDMONTON: PART 1

by

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RESEARCH MANAGEMENT DIVISION

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LIST OF SYMBOLS

B	Bulk Richardson Number
E	CO emission factor ($g \cdot vehicle^{-1} \cdot km^{-1}$)
E_o	CO emission factor at 24C ($g \cdot vehicle^{-1} \cdot km^{-1}$)
K	Mass diffusivity coefficient ($m^2 \cdot s^{-1}$)
K_R	Mass diffusivity coefficient at reference level z_R ($m^2 \cdot s^{-1}$)
K_{MR}	Momentum diffusivity coefficient at z_R ($m^2 \cdot s^{-1}$)
K_{HR}	Heat conductivity coefficient ($m^2 \cdot s^{-1}$)
K_V	Source mass diffusivity coefficient at z_R ($m^2 \cdot s^{-1}$)
k	Von Kàrmàn's Constant
L	Monin-Obukhov length (m)
m	Exponent in power-law wind speed profile
N	Percentage of daily motor vehicle traffic in 1 h
$\bar{N}$	Mean hourly percentage of motor vehicle traffic
n	Exponent in power-law diffusivity profile
Q	Line source strength ($g \cdot m^{-1} \cdot s^{-1}$)
q	Area source strength ($g \cdot m^{-2} \cdot s^{-1}$)
r	$(m - n + 2)$
s	$(m + 1)/r$
s_o	Value of s at current hour
T	Air temperature (C)
T_e	Ambient temperature factor for emission rate
U	Mean wind speed ($m \cdot s^{-1}$)

continued...

LIST OF SYMBOLS (CONTINUED)

U_R, U_2, U_3	Mean wind speeds at z_R, z_2, z_3 ($m \cdot s^{-1}$)
$\bar{U}$	Mean wind speed below z_R ($m \cdot s^{-1}$)
$\bar{U}_1, \bar{U}_2$	Mean wind speeds at geometric mean heights $\bar{z}_1, \bar{z}_2$ ($m \cdot s^{-1}$)
u_*	Friction velocity ($m \cdot s^{-1}$)
W	Stability factor
W_o	Stability factor for current hour
x	Distance upwind from receptor (m)
x_o	Travel distance of air for current hour (m)
x_e	Distance upwind from receptor to equivalent line source
y	Similarity-theory function
z	Height (m)
z'	Height relative to origin at z_o (m)
$\bar{z}_1, \bar{z}_2$	Geometric mean heights z_1 to z_2 ($\bar{z}_1$) and z_2 to z_3 ($\bar{z}_2$)
z_1, z_2, z_3	Heights of tower measurement levels (m)
z_R	Reference or CO receptor height
z_o	Roughness length (m)
α	Factor dependent on choice of Von Kàrmàn's Constant
β_M	Similarity-theory coefficient for momentum function
β_H	Similarity-theory coefficient for heat function
Γ	Gamma function
ζ'	Non-dimensional height expressed as z'/L
$\bar{\zeta}_1', \bar{\zeta}_2'$	$\bar{z}_1'/L$, $\bar{z}_2'/L$
ζ_2', ζ_3'	z_2'/L, z_3'/L

continued...

LIST OF SYMBOLS (CONCLUDED)

η	Similarity-theory function
θ	Potential temperature (^{o}K)
$\theta_1, \theta_2, \theta_3$	Potential temperatures (^{o}K) at z_1, z_2, z_3
$\Delta\theta$	Potential temperature difference (^{o}K) between z_3 and z_1
$\Delta\theta_1$	Potential temperature difference (^{o}K) between z_2 and z_3
$\Delta\theta_2$	Potential temperature difference (^{o}K) between z_1 and z_2
ρ	Air density ($kg \cdot m^{-3}$)
ϕ_M	Similarity-theory profile function for momentum
ϕ_H	Similarity-theory profile function for sensible heat
ψ	Air pollutant concentration ($g \cdot m^{-3}$ or ppm)
ψ_o, ψ_1	Air pollution concentration ($g \cdot m^{-3}$ or ppm) at current hour (ψ_o) or at previous hour (ψ_1)

SUMMARY

A numerical model for estimation of surface concentration of a conservative air pollutant such as CO was formulated for ground-level line or area source emissions. The model utilizes a well-known solution to the diffusion equation together with similarity-theory predictions for wind speeds and vertical diffusivity coefficients. The model assumes horizontal homogeneity in atmospheric structure and requires concurrent input data from a single meteorological tower having wind speed observations at 50 to 100 m and temperature differences between three tower levels. Because wind speeds rarely dropped below anemometer threshold speed at the top of the tower, the model avoids the difficulties often caused by below-threshold winds at standard (10 m) anemometer level.

Observed hourly mean CO concentrations on 14 d (328 h) with CO concentration maxima in excess of 6 ppm in downtown Edmonton in 1977 were selected for verification purposes. The total sample was divided into two subsamples, each of 7 d, and model performance was measured by correlation coefficients and by standard errors. The influence of ambient temperature, altitude, and heavy-duty motor vehicles on the CO emission factor for Edmonton were estimated from studies carried out elsewhere. The result was an emission factor of 77 $g \cdot vehicle^{-1} \cdot km^{-1}$ for 1977. In addition, a comprehensive inventory of emissions based on vehicle counts in various parts of the city was prepared for use in the model. The performance of the newly developed model was compared with those for three alternative simple box models which do not require meteorological tower data. Direct comparisons with the model of Leahey (1975) for Edmonton were not possible because of the lack of quantitative data on sensible heat release to the atmosphere.

The model yielded a correlation coefficient of 0.79 ± 0.01 (62% of total variance) for hourly-mean observed CO concentrations and a standard error of 1.9 ± 0.1 ppm. The correlation coefficient

was insensitive to possible choices of similarity-theory coefficients (Businger et al. 1971; Wieringa 1980), to the choice of heat or momentum diffusivity coefficients, and to the choice of roughness length. However, the standard error of estimates was sensitive to the specification of initial source dispersion. The model was consistent with a CO emission factor between 60 and 80 $g \cdot vehicle^{-1} \cdot km^{-1}$ for Edmonton in 1977.

Several possible model improvements were identified from analyses of large errors. These include: (1) measurements of initial source dispersion from motor vehicles within the city; (2) measurements of vertical temperature differences in the lowest 10 to 20 m in the city; (3) replacement of the power-law diffusivity profile by a profile which includes a non-zero diffusivity at the earth's surface; and (4) use of less than one-hour averages of meteorological tower data.

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1. INTRODUCTION

In an earlier experimental study of CO concentrations in the North Saskatchewan River valley in Edmonton (Hage 1979), many similarities were found in the concentration time changes within the valley and in the city above. Late evening or early morning concentration maxima were found in both places when skies were clear and prevailing winds dropped below 12 to 15 $km \cdot h^{-1}$. Large variations in the timing and magnitude of concentration maxima associated with morning and afternoon traffic peaks were observed in both places. It was concluded that one would have little prospect of understanding air pollution concentration changes in the valley unless one first understood the complex changes observed within the city above.

Urban pollution models for low-level area sources have been reviewed by Hanna (1975) who classified them as rollback, statistical, analytical, and numerical model types. Of these, the numerical models appeared to offer the greatest potential for assessment of the relative importance of various physical factors. For this reason, a numerical model was selected for application to Edmonton. Because meteorological data were available only from one surface weather station within the city (Edmonton Municipal Airport) and from one urban meteorological tower, it was necessary to assume horizontal homogeneity in all meteorological variables within the city. The model developed by Leahey (1975) for Edmonton was rejected because it requires unknown numerical values of the sensible heat released by the city. An earlier study (Hage 1972) of the Edmonton urban heat island strongly suggested that sensible heat release from solar heat stored within the city fabric was not negligible in any season except perhaps in severe cold spells.

2. MODEL DEVELOPMENT

2.1 DIFFUSION MODEL COMPONENT

The model to be described utilizes a known gradient transfer mathematical solution for crosswind line sources together with recent similarity-theory summaries of wind and temperature profiles in the atmospheric surface layer. The shortcomings of the gradient-transfer theory are well known; however, the theory works well for short-range diffusion from ground-level line and area sources, evidently because the scales of vertical turbulence are severely constrained by the earth's surface (Pasquill 1975). For this reason, the diffusive growth of the plume is accomplished by vertical scales of turbulence that are comparable to or smaller than the vertical scale of the plume.

A solution to the two-dimensional diffusion equation for concentration ψ:

$$U \frac{\partial \psi}{\partial x} = \frac{\partial}{\partial z} \left(K \frac{\partial \psi}{\partial z} \right) , \tag{1}$$

subject to power-law representation of vertical variations of wind speed U and vertical eddy diffusivity K,

$$U = U_R \left(\frac{z}{z_R} \right)^m , \qquad K = K_R \left(\frac{z}{z_R} \right)^n \tag{2}$$

was first presented by Roberts (unpublished, see Sutton 1953). In (2) U_R and K_R are the values of U and K at $z = z_R$. The boundary conditions are:

$$\psi \to 0 \quad \text{as} \quad x, z \to \infty$$

$$\psi \to \infty \quad \text{as} \quad x = z = 0$$

$$K \frac{\partial \psi}{\partial z} \to 0 \quad \text{as} \quad z \to 0, x > 0$$

The equation of conservation of mass is:

$$\int_0^\infty U\psi dz = Q \qquad x > 0 \tag{3}$$

The solution to (1), subject to conditions (2) and (3) is:

$$\psi = \frac{Qr}{U_R \Gamma(s)} \left(\frac{U_R}{r^2 K_R x}\right)^s z_R^{m - s(m-n)} \cdot$$

$$\exp - \left[\left(\frac{U_R}{r^2 K_R}\right) \frac{z_R^{n-m}}{x} z^r\right] \tag{4}$$

where: $r = m - n + 2 > 0$

$s = (m + 1)/r$

2.2 METEOROLOGICAL DATA

The meteorological data available for the evaluation of unknown parameters in (4) consisted of temperature differences between three levels, $z_3 = 91.4$ m, $z_2 = 45.7$ m, and $z_1 = 10$ m, along with wind speeds at z_3, on a tower within the city of Edmonton about 3 km northwest of the city centre. From these data hourly mean bulk Richardson Numbers B were computed, where:

$$B = \frac{g}{T} \frac{\partial\theta/\partial z}{U^2} \bar{z}^2 \tag{5}$$

where g is the acceleration of gravity, T is mean temperature, $\partial\theta/\partial z$ is the vertical gradient of potential temperature, U is wind speed at the highest level, and $\bar{z}$ is the geometric mean height between the two levels of measurement. The vertical gradient of θ in the layer from z_1 to z_3 was approximated by (Panofsky 1965):

$$\frac{\partial\theta}{\partial z} \doteq \frac{\theta_3 - \theta_1}{(z_1 z_3)^{\frac{1}{2}} \ln z_3/z_1}$$

This equation is exact for logarithmic functions of height. A similar formula was used for the potential temperature gradients in the lowest and highest tower layers.

According to Golder (1972) the bulk Richardson Number B is related to the nondimensional height $\zeta' = \bar{z}'/L$, where L is the Monin-Obukhov length, by:

$$B = \frac{\zeta'}{y^2\ (\ell n\ \bar{z}/z_o - \eta)^2} \qquad \text{(unstable)} \tag{6}$$

where: $\zeta' = z - z_o$

$$\eta = 2\ \ell n[(1 + y)/2] + \ell n[(1 + y^2)/2] - 2\ \tan^{-1} y + \pi/2$$

$$y = (1 - \beta_m \zeta')^{\frac{1}{4}}$$

$$B = \frac{\zeta'(1 + \beta_m \zeta')}{(\ell n\ \bar{z}/z_o + \beta_m \zeta')^2} \qquad \text{(stable)} \tag{7}$$

Given B, equations (6) and (7) were solved for L. Given L, the required wind speed U_R was obtained from:

$$\frac{U_R}{U_3} = \frac{\ell n\ z_R/z_o - \eta(\zeta_R')}{\ell n\ z_3/z_o - \eta(\zeta_3')} \qquad \text{(unstable)} \tag{8}$$

$$\frac{U_R}{U_3} = \frac{\ell n\ z_R/z_o + \beta_m \zeta_R'}{\ell n\ z_3/z_o + \beta_m \zeta_3'} \qquad \text{(stable)} \tag{9}$$

The exponent m in the wind speed power law (2) was obtained by fitting the power law to the wind speeds U_R and U_3. These choices were made because U_3 is an observed speed and because U_R is at receptor height. For purposes of sensitivity tests the remaining parameter K_R was evaluated by equating the eddy diffusivity for mass to either the momentum diffusivity K_{MR} or to the eddy

conductivity K_{HR} where:

$$K_{MR} = \frac{k\, u_* z_R}{\phi_M} \quad \text{and} \quad K_{HR} = \frac{k\, u_* z_R}{\phi_H} \tag{10}$$

where:

$$\phi_M = (1 - \beta_M \zeta')^{-\frac{1}{4}} \qquad \text{(unstable)}$$

$$\phi_M = (1 + \beta_M \zeta') \qquad \text{(stable)}$$

$$\phi_H = \alpha(1 - \beta_H \zeta')^{-\frac{1}{2}} \qquad \text{(unstable)}$$

$$\phi_H = (\alpha + \beta_H \zeta') \qquad \text{(stable)} \tag{11}$$

In tests to follow, the coefficients α, β_M, and β_H given by Businger et al. (1971) and by Wieringa (1980) were tested separately. The numerical values of these coefficients are listed in Table 1. The friction velocity u_* was computed from:

$$u_* = \frac{k\bar{U}_2}{\ell n\, \bar{z}_2/z_o - \eta(\zeta_2')} \qquad \text{(unstable)}$$

or (12)

$$u_* = \frac{k\bar{U}_2}{\ell n\, \bar{z}_2/z_o - \beta_M \bar{\zeta}_2'} \qquad \text{(stable)}$$

Similar formulas with appropriate changes in heights were used for u_* in the lowest and highest tower layers.

The preceding formulas represent semi-empirical relations for a similarity description of the atmospheric surface layer. There can be no doubt that one of the major assumptions of this similarity theory, i.e., horizontal homogeneity, is violated in an urban area. However, in this application the horizontal inhomogeneities are not as extreme as they appear over the city as a whole because pollutant concentrations depend primarily on

Table 1. Similarity function coefficients

Source	β_M		β_H		α	
	Unstable	Stable	Unstable	Stable	Unstable	Stable
Businger et al. (1971)	15	4.7	9	4.7	0.74	0.74
Wieringa (1980)	22	6.9	13	9.2	1	1

the wind and turbulence structure within a few city blocks upwind of the receptor. In any case, one of the main purposes of the present study was to test the possibility that the advantage gained in using one of the best available formulations for turbulence in horizontally-homogeneous diabatic surface layers more than compensated for errors caused by application to inhomogeneous terrain.

In stable air as $L \to 0$, $B \to 1/\beta_M$ (a constant), and $K_R \to 0$. In this limit the wind profile becomes linear ($m = 1$) and the power-law approximation becomes exact. The implication is that vertical turbulent diffusion terminates except for mixing which results from the release of heat of combustion and mechanical stirring by motor vehicles. In order to account for this initial source dispersion it was assumed that $K_R \to K_V$ as $L \to 0$, where K_V was taken to be a constant minimum value.

2.3 EMISSION DATA

According to Alberta Environment (1973) all major point sources of CO in Edmonton were virtually eliminated in 1973 after installation of CO boilers at the city refineries. Remaining sources other than motor vehicles (natural gas combustion, aircraft, incinerators, locomotives, and power plants) accounted for only 0.6% of the total. Therefore, for present purposes, it was assumed that all CO was emitted by motor vehicles.

Mean annual weekday traffic flow data for Edmonton in 1977 were transferred from a street map (City of Edmonton 1978) to grid squares which increased in grid length from 100 m in central Edmonton to 1000 m at distances greater than 500 m from the receptor in each of eight directions. These data were supplemented by traffic flow estimates for suburban streets with daily counts below 3000 vehicles. Vehicle counts were multiplied by the distance travelled within each grid square and divided by area and time to yield units of vehicle ($km \cdot m^{-2} \cdot s^{-1}$). The results, averaged over eight directions, are shown in Figure 1. The computed source strength

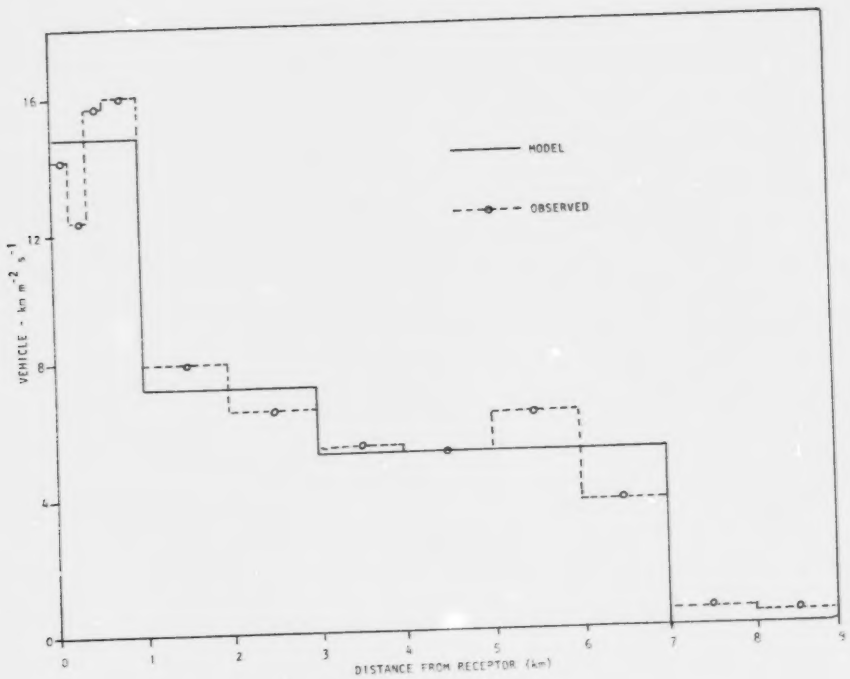

Figure 1. Observed and simulated motor vehicle flow rates for Edmonton in 1977 upwind of monitoring unit EDMU and averaged for all wind directions.

variations with distance were simulated in the model by the step function shown by the solid line in Figure 1.

The urban area source of CO can be interpreted as a succession of elementary crosswind line sources having strength

$$\Delta Q = q(x)\Delta x \tag{13}$$

where $q(x)$ is the area source strength for an alongwind strip of width 1 m and length Δx. The ordinate in Figure 1 can be converted directly to $q(x)$ by multiplication by the emission factor E for CO ($g \cdot vehicle^{-1} \cdot km^{-1}$). The result is an average daily area source strength $q(x)$ in units $g \cdot m^{-2} \cdot s^{-1}$. The receptor data available for model testing were hourly mean concentrations ψ. Therefore, $q(x)$ was multiplied by a factor $N/\bar{N}$, where N is the percentage of daily motor vehicle traffic at any hour and $\bar{N}$ is the mean hourly percentage. Values of N valid for Edmonton in 1977 are shown in Figure 2. A map showing Edmonton city boundaries in 1977, the central CO monitoring unit (EDMU), the Edmonton Municipal Airport (YXD), and the meteorological tower (A) is shown in Figure 3.

The automobile emission factor E for CO for Canada for 1977 was estimated by Taylor (1973) to be 64 $g \cdot vehicle^{-1} \cdot km^{-1}$. This includes a constant temperature factor of 1.3 which converts E from an ambient temperature of 21°C to E for a mean annual temperature derived from climatological data for Toronto and Montreal. In the present study, a variable temperature correction factor T_e related to observed hourly mean temperatures at Edmonton Municipal Airport was used. The formula for T_e was adapted from United States Environmental Protection Agency (1975).

$$T_e = 1.54 - 0.022\ T \tag{14}$$

where T is the observed temperature (°C). The reference temperature ($T_e = 1$) in (14) is 24°C. Therefore, the appropriate value of E for CO in Edmonton in 1977 was assumed to be $E = T_e E_o$, where E_o is the emission factor for 24°C ($E_o = 46\ g \cdot vehicle^{-1} \cdot km^{-1}$). According to

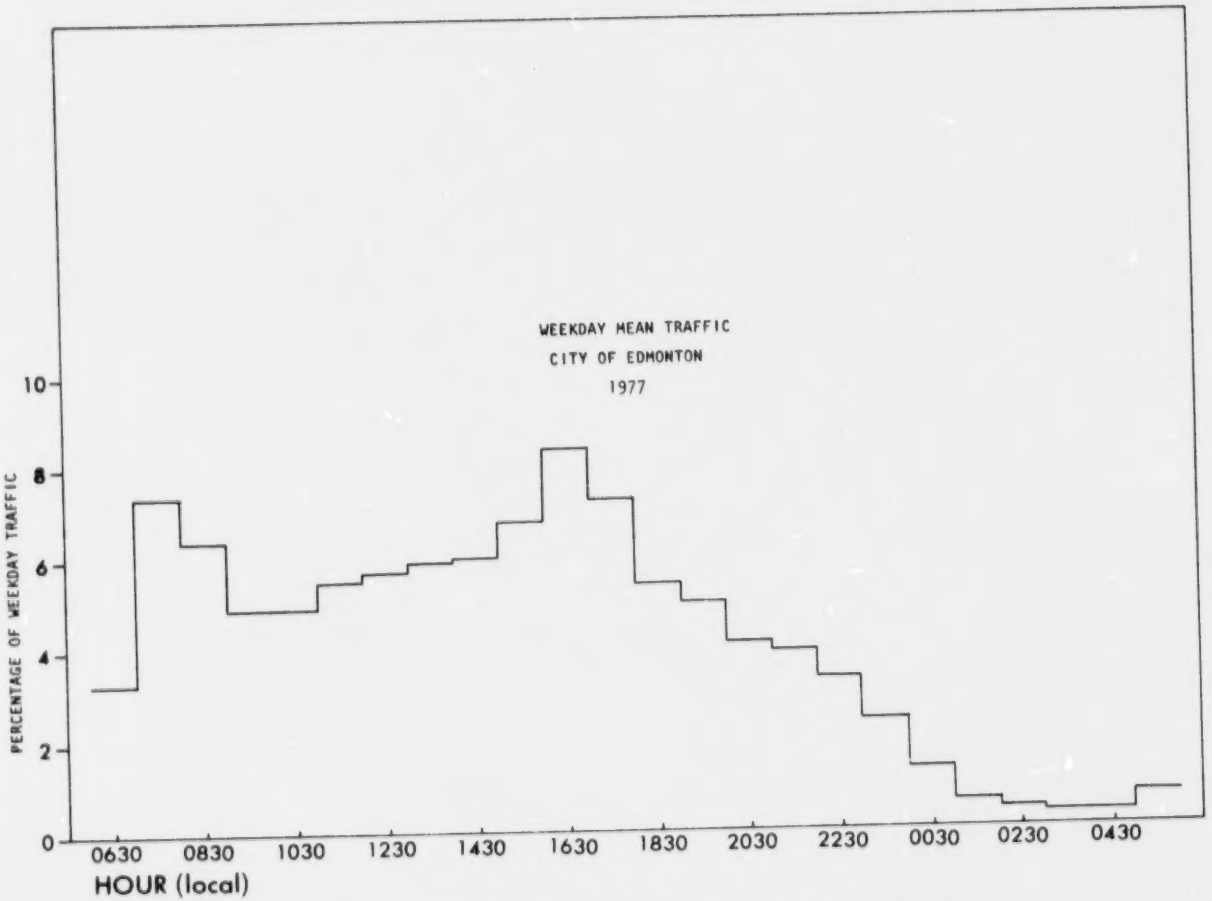

Figure 2. Diurnal variations in weekday motor vehicle traffic in Edmonton.

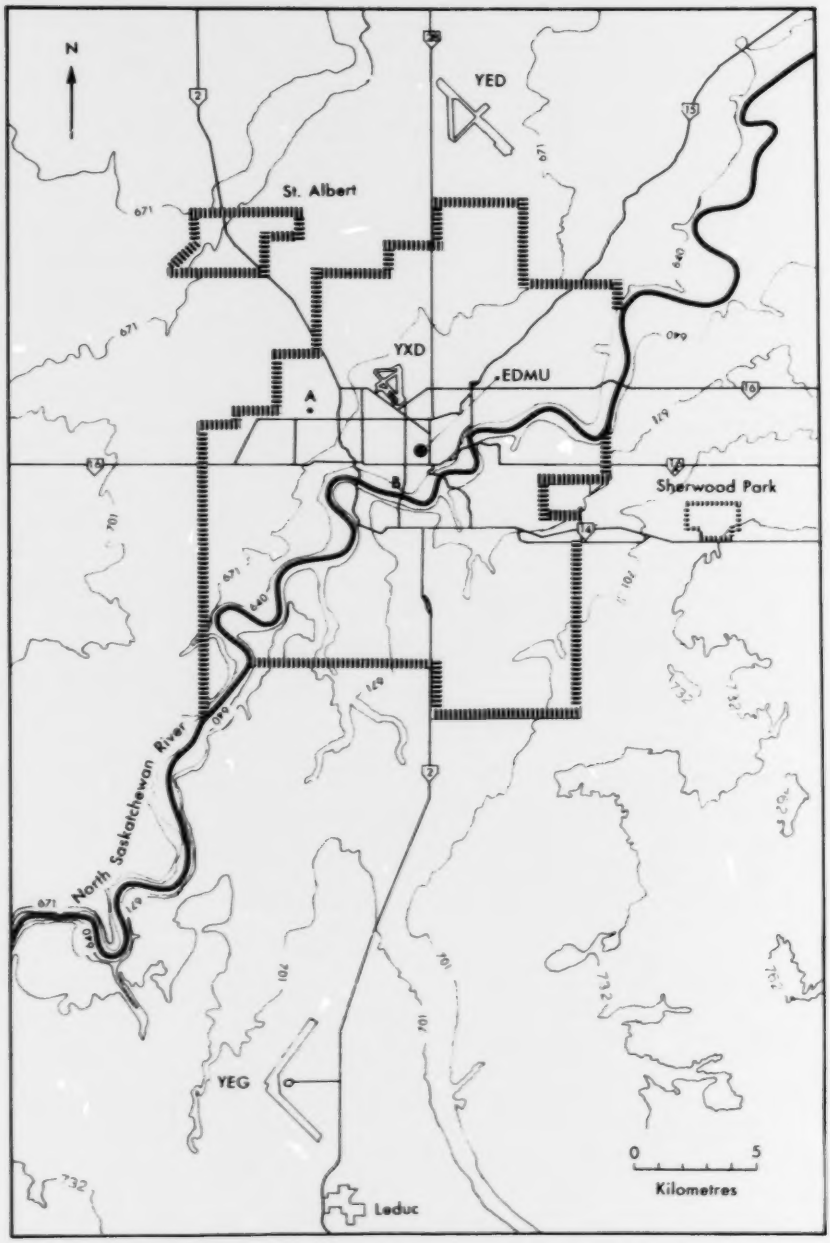

Figure 3. Edmonton city boundaries in 1977, CO monitoring unit (EDMU) and meteorological tower (A) used in this study, and Edmonton Municipal Airport (YXD).

Marcum and Hanna (1979), (14) may not be valid for low ambient temperatures because most excess emissions occur during engine warm-up.

Although automobiles and light-duty trucks constitute the dominant sources of CO, some contributions are added by heavy-duty trucks and for buses are available for Edmonton but these are not classified according to fuel type. Emission factors for CO are much greater for heavy-duty gasoline-powered trucks than for heavy-duty diesel-powered trucks, and, therefore, fuel-type classification of large vehicles is essential. However, according to United States Environmental Protection Agency (1975), the influence of variations in typical mixtures of vehicle types on the emission factor is relatively small. Table 2 was prepared from data in their report and refers to the 1972 US emission factors for CO for an ambient temperature of 24°C, 20% cold operation, and mean vehicle speed of 21.6 km h^{-1}. According to Table 2, the addition of heavy-duty trucks to the vehicle mix for a suburban residential area increased the emission factor by 8.4% from 43.8 to 47.5.

Another important variable which may increase the emission factor for automobiles in Edmonton by a substantial amount is the effect of altitude. Emission factors for sea level and 1500 m were reported by United States Environmental Protection Agency (1975). Linear interpolation resulted in a factor of 1.54 for Edmonton's altitude of 670 m. The final value of E_o for use in the model was:

$$E_o = 46 \times 1.54\ (1 + 0.084) = 77\ g \cdot vehicle^{-1} \cdot km^{-1}$$

which includes estimates of both altitude and vehicle mix effects. It is possible that $E_o = 77$ is slightly low because of the fact that the percentage of large automobiles in Edmonton is somewhat greater than that for eastern Canadian cities (Polak 1979). However, no adjustment was made for lack of quantitative data.

The emission factor used in the present study is much larger than the value of 23 $g \cdot vehicle^{-1} \cdot km^{-1}$ used by Paterson and

Table 2. Effects of vehicle mix on CO emission factors.

Source	Vehicle Type[a] (%)				Emission Factor
	A	L	HG	HD	($g \cdot vehicle^{-1} \cdot km^{-1}$)
National Average	80.4	11.8	4.6	3.2	47.5
Central City	63.0	32.0	2.5	2.5	48.6
Suburbs	88.2	11.8	0.0	0.0	43.8

[a] A - Automobile
L - Light-duty trucks
HG - Heavy-duty gasolene trucks
HD - Heavy-duty diesel trucks

Hage (1979). The latter was a tentative estimate by Alberta Environment which did not include temperature and altitude effects. Nevertheless, it yielded excellent results when applied to CO concentration calculations in downslope flow (Paterson and Hage 1979). From the results of the present study it is clear that initial source dispersion, rather than atmospheric dispersion, dominated at the distances of 33 and 60 m involved in the valley experiment. Evidently an underestimate of emission factor combined with an underestimate of initial source dispersion combined to give a reasonable concentration estimate in Paterson and Hage (1979). Such fortuitous results illustrate the risks involved in dependence on the results of a single experiment. The results of this experiment are examined in more detail in a later section.

2.4 TIME-DEPENDENT ADVECTION COMPONENT

Hourly advection distances were calculated using the mean wind speed between the earth's surface and the receptor height of 8.5 m from the power-law wind profile. Using hourly mean values, (4) is valid for mean wind speeds greater than or equal to $1.9\ m \cdot s^{-1}$. In lighter winds, a time interval in excess of 1 h is required for air to reach the receptor from the city boundary and it became necessary to take into account hourly changes in wind speed, stability, and emission rates.

The city source was simulated by a series of infinite crosswind line sources at 100 m intervals from 100 m to 7 km. Numerical tests showed that the height-dependent exponential factor in (4) was near unity for a receptor height of 8.5 m in central Edmonton. With this simplification (4) becomes:

$$\psi = WQx^{-s} \tag{15}$$

where

$$W = \frac{z_R^{m - s(m - n)}\, r}{U_R \Gamma(s)} \left(\frac{U_R}{r^2 K_R} \right)^s \tag{16}$$

If subscripts o and 1 are used to denote current hour and preceding hour values, respectively, then the contribution to the receptor due to preceding hour sources were calculated using an effective source distance x_e given by:

$$\psi_1(x = x_1) = W_o Q_1 x_e^{-s_o} \tag{17}$$

The concentration ψ_o at the receptor ($x = 0$) from sources of the preceding hour was calculated from:

$$\psi_o(x = 0) = \left(\frac{x_e}{x_o + x_e}\right)^{s_o} \psi_1 \tag{18}$$

This procedure was generalized for any number of preceding hours and for all combinations of hours dominated by initial source dispersion or by atmospheric dispersion. The first calculation of concentration from any hour using (15) was subjected to the condition that concentration could not exceed that given by minimum values of s and $K_R = K_V$. When K_V was used, concentrations were advected without change following the initial hour of plume stretching. This corresponded to $x_e = \infty$ in (18) which results from the limiting case $K_R = 0$ (no atmospheric vertical diffusion).

2.5 SOURCE DISPERSION

Initial source dispersion was simulated in the model by:

$$\psi = \frac{Qr}{U_R \Gamma(s)} \left(\frac{U_R}{r^2 K_V x}\right)^s z_R^{m - s(m - n)} \tag{19}$$

where K_V was a vertical mass diffusion coefficient which simulated the effects of vertical spreading of exhaust plumes under the combined influences of buoyant rise and mechanical stirring by vehicles. Estimates of K_V were derived from experiments carried out in the North Saskatchewan River valley in Edmonton. Supercritical

bulk Richardson numbers were observed in both experiments. Therefore, it was assumed that vertical atmospheric turbulence was negligible.

In the first experiment, described by Paterson and Hage (1979), a downslope (drainage) wind prevailed. Such winds are known to have maximum speeds below 1 m and to decrease slowly with height near the base of North Saskatchewan River valley slopes. The wind was simulated in the model by $m = 0$ (no variation of wind speed with height) and $U_R = 0.4\ m \cdot s^{-1}$ at $z_R = 0.8$ m (measured). With the choise $n = 0$ (K_V constant with height), $r = 2$ and $s = \frac{1}{2}$. The source consisted of a single crosswind line source (River Road) at distances of 33 m and 60 m from the CO monitor. A traffic flow rate of 500 vehicles$\cdot h^{-1}$ and an emission factor of 110 g$\cdot$(vehicle$\cdot$km)$^{-1}$, corresponding to an ambient temperature of 5°C were used. The derived values of K_V were 0.75 $m^2 \cdot s^{-1}$ ($x = 33$ m) and 0.79 $m^2 \cdot s^{-1}$ ($x = 60$ m). The ratio of the two observed concentrations depends only on s and yielded a value of $s = 0.55$ in reasonable agreement with the assumed value of $s = \frac{1}{2}$.

The second experiment was carried out near the base of Groat Ravine on 1980 August 25. The prevailing wind was from the same direction (NW) as the down-ravine or drainage wind and conditions remained steady for more than 5 h. Measured wind speeds at two heights yielded $m = 0.31$ and $U_R = 0.24\ m \cdot s^{-1}$ at $z_R = 0.8$ m assuming $n = 0$, $r = 2.3$, and $s = 0.57$. Over a 5 h period, from 2000 to 0100, a total of 6700 vehicles followed a 1.2 km roadway from the top to the base of the ravine. The lateral spreading of the vehicle plume between the base of the ravine and the meteorological tower was estimated from the standard deviation of wind direction fluctuations at 7.5 m. An emission factor of 110 g$\cdot$(vehicle$\cdot$km)$^{-1}$ for the ambient temperature of 5°C was used. The derived value of K_V from CO concentrations measured at 0.4 m was 0.88 $m^2 \cdot s^{-1}$.

In the second experiment described above, CO concentrations were measured at a height of 4.8 m as well as 0.4 m. The

exponential factor in (4) was used together with $K_V = 0.88\ m^2 \cdot s^{-1}$ to calculate an effective distance over which vertical spreading of the vehicle plume occurred in very stable air. This distance was found to be 7.5 m or slightly more than two average vehicle lengths. In other words, vertical diffusion due to buoyancy and mechanical stirring by vehicles evidently occurred within the first 10 m of air travel.

2.6 ROUGHNESS LENGTH

The only remaining undetermined model parameter is the roughness length z_o. Nine samples of near-neutral stability ($L < -1000$ or $L > +5000$) wind profiles, each of 1 h duration, and each having wind directions not including those from the central business district of tall buildings were selected. For lack of low-level tower wind speeds it was necessary to use 10 m wind speeds from the Municipal Airport about 2 km from the tower. The computed mean value was $z_o = 0.21 \pm 0.12$ m. Nine samples of wind profiles with wind directions from the central business district to the tower (120^o to 135^o) were used to estimate the roughness length of the area of tall buildings. The result was $z_o = 1.1 \pm 0.83$ m. The large standard deviation of this estimate was attributed to the need for large stability corrections in most samples. Two hours with near-neutral stability ($L = -14000$, $L = -4700$) yielded values of $z_o = 2.2$ m and $z_o = 1.9$ m, respectively.

3. RESULTS

3.1 CASE SELECTION

The receptor EDMU was moved to its present location at 10255 - 104 Street, Edmonton in December 1976. Urban meteorological tower observations were terminated in November 1977 so that approximately 12 mo of data were available for test purposes. CO concentration maxima ≥ 8.5 ppm were reported at EDMU on 16 non-holiday weekdays for which meteorological tower data were available in this 12-mo period. Two of these days were adjacent to other days with similar concentration maxima. The remaining 14 d (329 h) with 21 CO concentration maxima in excess of 6.5 ppm (50% of regulatory limits) were selected for test purposes (Table 3).

Tower temperature differences were abstracted at 5 min intervals and wind speeds and directions were abstracted at 10 min intervals. Hourly mean values of $\Delta\theta$, $\Delta\theta_1$, $\Delta\theta_2$, and U_3, centred on the half-hour to coincide with CO concentration data, were computed from the raw data. Wind speeds dropped below anemometer threshold 1.2% of the time at 91.4 m on the tower and 21.0% of the time at 10 m at Edmonton Municipal Airport. A value of 0.7 $m \cdot s^{-1}$ (midpoint between 0 and the threshold speed of the anemometer) was used on these occasions for U_3. Airport wind data were not needed for the model.

3.2 MODEL VERIFICATION AND SENSITIVITY STUDIES

Verification by correlation coefficients and by standard errors was carried out for the days listed in Table 3. The total sample of 14 d was divided into 7-d subsamples consisting of alternate days as a test of the stability of the two measures of performance. It is apparent from Table 3 that the magnitudes of CO concentration maxima varied with season. Alternate day samples were used in an attempt to reduce seasonal differences between the two subsamples. Correlation coefficients were computed also for three alternative simple models. The first of these (N) includes

Table 3. Test sample.

Date	CO Concentration Maxima						No. Hours
	Morning		Afternoon		Evening		
	ψ(ppm)	Hour	ψ(ppm)	Hour	ψ(ppm)	Hour	
13,14 Apr.	9.0	0830	2.5	1630	No Maxima		24
25,26 Apr.	10.5	0830	3.0	1630	3.0	2130	24
9,10 May	6.5	0830	3.5	1630	9.0	2330	24
20,21 May	3.5	0830	4.0	1630	8.5	2330	24
17,18 June	5.5	0830	4.0	1630	8.5	0130	24
15,16 July	4.5	0930	3.0	1630	8.5	0230	24
9,10 Aug.	3.0	0830	3.5	1630	7.0	0230	24
16,17 Aug.	9.0	0830	2.5	1630	No Maxima		24
19,20 Aug.	9.0	0830	2.5	1630	2.0	2230	24
12,13 Oct.	7.0	0930	9.0	1830	ND	ND	24
18,19 Oct.	8.0	0730	8.0	1630	11.0	2230	17[a]
28,29 Oct.	10.0	1130	7.5	1630	No Maxima		24
1,2 Nov.	9.0	0930	7.0	1730	5.0	2230	24
4,5 Nov.	12.0	0830	10.0	1830	4.5	0030	24

[a] CO data missing for 7 h.

only the effects of varying traffic flow rates and is equivalent to a box model with constant wind speed, constant box depth, and constant emission factor. The second (NT_e) includes the effects of ambient temperature variations on the emission factor and is equivalent to a box model with constant wind speed and constant box depth. The third and fourth (NT_e/U and NT_e/U_3), where U is the 10 m wind speed from Edmonton Municipal Airport and U_3 is the tower wind speed at 91.4 m, are equivalent to box models with constant box depths. Meteorological tower data are not required for the first three of these models. Standard errors were not computed for the models for lack of knowledge of the appropriate mean box depth.

Hours with supercritical bulk Richardson numbers ($B > 1/\beta_M$, no atmospheric turbulence in the vertical direction) were selected for tests of model sensitivity to K_V, the initial source vertical diffusion coefficient. The results are shown in Table 4 (correlation coefficients) and Table 5 (standard errors of estimates). The highest correlations and the lowest standard errors were found for $K_V = 1.25$, a value much larger than the values of $K_V = 0.75$ to $K_V = 0.88$ derived earlier from valley measurements. A detailed analysis of the data revealed that K_V in the model served not only to simulate initial source dispersion but also to compensate for the lack of tower data on atmospheric stability in the lowest 10 to 20 m. Shortly after sunrise, solar radiation begins to destroy the nocturnal inversion over the city at low levels. However, the existence of such a layer was not evident in the tower data until it reached the middle tower level at 45.7 m. A rather large value of K_V (the minimum value of vertical diffusion coefficient in the model) evidently compensated in part for the lack of tower data at low levels. In order to test this hypothesis two values of K_V were used. Between sunset and sunrise $K_V = 0.75$ and between sunrise and sunset $K_V = 1.5$. The results are shown under the heading *Variable* K_V in Tables 4 and 5. The increase in correlation coefficient and reduction in standard error illustrate the need for low-level temperature differences at certain hours of the day in this application.

Table 4. Correlation sensitivity to K_V (supercritical bulk Richardson number).

Roughness Length (m)	K_V ($m^2 \cdot s^{-1}$)	Correlation Coefficients		
		Sample 1	Sample 2	Total Sample
1.0	0.50	0.51	0.67	0.63
	0.75	0.52	0.69	0.65
	1.00	0.54	0.69	0.66
	1.25	0.56	0.70	0.67
	1.50	0.56	0.70	0.67
	1.75	0.56	0.70	0.67
	Variable	0.65	0.83	0.78
Sample size (h)		15	16	31

Table 5. Standard error sensitivity to K_V (supercritical bulk Richardson number).

Roughness Length (m)	K_V ($m^2 \cdot s^{-1}$)	Standard Errors (ppm)		
		Sample 1	Sample 2	Total Sample
1.0	0.50	4.58	4.64	4.61
	0.75	2.74	2.94	2.84
	1.00	2.02	2.36	2.20
	1.25	1.91	2.29	2.11
	1.50	2.10	2.41	2.26
	1.75	2.36	2.58	2.48
	Variable	1.47	1.77	1.63
Sample size (h)		15	16	31

The results of model sensitivity tests to K_V for all hours in the 14 d test sample are shown in Tables 6 and 7. For purposes of these tests the similarity-theory coefficients of Wieringa (1980) were used along with the momentum atmospheric diffusion coefficient, n = 0 (vertical diffusion coefficient constant with height), roughness length z_o = 1.0 m, and bulk Richardson numbers derived from temperature differences in the lowest tower layer (10 m to 45.7 m). The sensitivity of the model to each of these parameters is discussed later. From Table 6 correlation coefficients were found to be fairly insensitive to choices of K_V over a wide range of values. Standard errors were smallest for $K_V \geq 1.25$. The model bias at $K_V = 1.0\ m^2 \cdot s^{-1}$ was +0.5 ppm. However, when the model was run with $K_V = 1.0\ m^2 \cdot s^{-1}$ and n = 1 - m, the correlation coefficient and standard error for the total sample were similar (0.77, 1.8 ppm) but the bias was -0.3 ppm. Therefore, there appears to be no evidence of an appreciable error in the emission factor at the reference temperature of 24°C (E_o = 77 g·(vehicle km)$^{-1}$).

Model sensitivity to roughness length, advection wind speed, vertical variations in diffusion coefficient as measured by n, the exponent in the diffusivity power law, and choice of tower temperature differences for evaluation of atmospheric stability, is illustrated in Tables 8 and 9. A value of $K_V = 1.0\ m^2 \cdot s^{-1}$ was used in these tests. Correlation coefficients and standard errors for all hours in the 14 d sample were found to be insensitive to roughness length over the range z_o = 0.2 m to z_o = 1.5 m. For this reason it appears unlikely that the observed roughness change from z_o = 0.2 m outside the central business district to z_o = 1.0 m in the central business district has any important effect on model performance. A small improvement in results occurred when the mean wind speed between the earth's surface and the CO monitor ($\bar{U}$) was used instead of the wind speed U_R at the height of the monitor. A large improvement in results occurred when temperature differences were taken from the lowest tower levels rather than from 10 m and 91.4 m. This supports the earlier finding regarding the importance

Table 6. Correlation sensitivity to K_V (all hours).

Roughness Length (m)	K_V ($m^2 \cdot s^{-1}$)	Correlation Coefficients		
		Sample 1	Sample 2	Total Sample
1.0	0.50	0.76	0.77	0.77
	0.75	0.77	0.79	0.79
	1.00	0.77	0.80	0.79
	1.25	0.76	0.79	0.78
	1.50	0.75	0.77	0.77
	1.75	0.74	0.76	0.76
Sample size (h)		161	168	329

Table 7. Standard error sensitivity to K_V (all hours).

Roughness Length (m)	K_V ($m^2 \cdot s^{-1}$)	Standard Errors (ppm)		
		Sample 1	Sample 2	Total Sample
1.0	0.50	2.65	3.09	2.88
	0.75	2.06	2.31	2.19
	1.00	1.77	1.98	1.88
	1.25	1.65	1.85	1.76
	1.50	1.61	1.84	1.73
	1.75	1.60	1.87	1.74
Sample size (h)		161	168	329

Table 8. Model verification (all hours).

Roughness Length (m)	Advection Wind	n (atmos.)	Tower Levels for $\Delta\theta$	Correlation Coefficients		
				Sample 1	Sample 2	Total Sample
0.2	$\bar{U}$	0	z_2, z_1	0.77	0.79	0.79
0.5	$\bar{U}$	0	z_2, z_1	0.77	0.80	0.79
1.0	$\bar{U}$	0	z_2, z_1	0.77	0.80	0.79
1.5	$\bar{U}$	0	z_2, z_1	0.77	0.79	0.79
1.0	U_R	0	z_2, z_1	0.74	0.77	0.76
1.0	$\bar{U}$	0	z_3, z_1	0.65	0.68	0.67
1.0	$\bar{U}$	1 - m	z_2, z_1	0.76	0.76	0.77
Box Models						
N				0.32	0.41	0.37
NT_e				0.38	0.52	0.46
NT_e/U				0.55	0.65	0.62
NT_e/U_3				0.49	0.47	0.48
Sample size (h)				161	168	329

Table 9. Model verification (all hours).

Roughness Length (m)	Advection Wind	n (atmos.)	Tower Levels for $\Delta\theta$	Standard Errors (ppm)		
				Sample 1	Sample 2	Total Sample
0.2	$\bar{U}$	0	z_2, z_1	1.79	1.98	1.89
0.5	$\bar{U}$	0	z_2, z_1	1.79	1.97	1.89
1.0	$\bar{U}$	0	z_2, z_1	1.77	1.98	1.88
1.5	$\bar{U}$	0	z_2, z_1	1.76	1.97	1.87
1.0	U_R	0	z_2, z_1	1.87	2.16	2.02
1.0	$\bar{U}$	0	z_3, z_1	2.32	3.35	2.89
1.0	$\bar{U}$	1 - m	z_2, z_1	1.62	1.98	1.81
Sample size (h)				161	168	329

of data on atmospheric structure at low levels. The use of n = 0 (diffusivity constant with height) gave slightly better results than n = 1 - m in the power law for K. The relation n = 1 - m results from imposing the condition of constant shear stress on the power laws for U and K. The failure of n = 1 - m, i.e., vertical diffusivity variations, to improve model results is attributed to the fact that $K = K_R(z/z_R)^{1-m}$ implies that K = 0 at z = 0, rather than $K = K_V$ at z = 0. Evidently there is a need for a new mathematical solution with non-zero K at z = 0 for application of the diffusion equation to problems that involve significant initial source diffusion at ground level.

On the basis of the correlation coefficients in Table 8 it is concluded that the inclusion of a temperature-dependent emission factor and the inclusion of variable wind speeds in a simple box model both improved the performance of such a model. Traffic flow (source strength) variations accounted for about 14% of the total variance of hourly CO concentrations. Emission factor variations with temperature accounted for an additional 8% of the variance. Plume stretching in variable winds raised the explained variance to 38%. The newly developed diffusion model, which included these variables as well as vertical atmospheric diffusion, initial source diffusion, and time-dependent advection, accounted for 62% of the total variance. It is interesting to note in Table 8 that, despite the rarity of calm winds at 91.4 m, the wind speed U_3 added little to the performance of the box model NT_e. In other words, the influence of atmospheric stability variations on wind speeds in the lower atmosphere was found to be important.

Model verification results for all hours with $B < 1/\beta_M$, i.e., for all hours not involving initial source dispersion only in the 14 d test sample, are shown in Tables 10 and 11. For purposes of these tests the roughness length was chosen to 1.0 m and $K_V = 1.0\ m^2 \cdot s^{-1}$. Bulk Richardson numbers were derived from the lowest tower layer. For both sets of similarity-theory coefficients tested, the correlation coefficients were highest and the standard

Table 10. Model verification (hours with $B < 1/\beta_M$).

Similarity Coefficients	K_R (atmos.)	n	Correlation Coefficients		
			Sample 1	Sample 2	Total Sample
Wieringa (1980)	Momentum	0	0.73	0.79	0.77
Wieringa (1980)	Heat	0	0.74	0.78	0.77
Wieringa (1980)	Momentum	1 - m	0.70	0.76	0.74
Wieringa (1980)	Constant ($1.0\ m^2 \cdot s^{-1}$)	0	0.72	0.69	0.71
Businger et al. (1971)	Momentum	0	0.73	0.74	0.74
Businger et al. (1971)	Heat	0	0.74	0.77	0.76
Sample size (h)			137	141	278

Table 11. Model verification (hours with $B < 1/\beta_M$).

Similarity Coefficients	K_R (atmos.)	n	Standard Errors (ppm)		
			Sample 1	Sample 2	Total Sample
Wieringa (1980)	Momentum	0	1.73	1.82	1.78
Wieringa (1980)	Heat	0	1.65	1.69	1.67
Wieringa (1980)	Momentum	1 - m	1.54	1.76	1.65
Wieringa (1980)	Constant ($1.0\ m^2 \cdot s^{-1}$)	0	2.45	2.68	2.57
Businger et al. (1971)	Momentum	0	1.92	2.14	2.04
Businger et al. (1971)	Heat	0	1.55	1.69	1.63
Sample size (h)			137	141	278

errors were smallest for the vertical turbulent heat diffusion coefficient. However, the differences were small and were not considered to be significant on the basis of these tests. There was no significant difference in test results based on Wieringa (1980) and Businger et al. (1971) similarity-theory coefficients. Positive bias values (predicted mean minus observed mean concentrations) of +0.35 (heat) and +0.50 (momentum) were found with Wieringa (1980) coefficients. The corresponding bias values for Businger et al. (1971) coefficients were +0.23 (heat) and +0.80 (momentum). The use of a constant value of vertical turbulent diffusion coefficient of 1.0 $m^2 \cdot s^{-1}$ reduced the overall correlation from 0.77 to 0.71. A similar drop in correlation occurred when a constant atmospheric diffusion coefficient of 1.75 $m^2 \cdot s^{-1}$ was used.

4. CONCLUSIONS

A numerical model was formulated for estimation of low-level concentrations of non-reactive air pollutants from surface line or area sources in terms of source and meteorological parameters. The model combines a classical solution to the diffusion equation with similarity theory for the effects of atmospheric stability on wind speeds and diffusion coefficients. Supercritical bulk Richardson number conditions are treated as a limiting form of the diffusion model. The model incorporates time-dependent advection, stability-dependent wind speeds and vertical turbulent diffusion coefficients, temperature-dependent emission factors, and an effective vertical diffusion coefficient for initial exhaust dispersion from motor vehicles. Its advantages are that all model parameters are well defined and measureable, and that the model appears to cope successfully with the problems of very light wind speeds and supercritical bulk Richardson number conditions. Its main disadvantage is that it requires data from a nearby meteorological tower.

The model was tested on 329 h of CO concentrations measured between April and November in the central business district of Edmonton in 1977. It was concluded that:

1. The new model accounted for 62% of the observed total variance of 6.9 $(ppm)^2$ with a root-mean-square error of 1.9 ppm. Traffic flow variations (14%), emission factor variations with ambient temperature (8%), and plume stretching in variable winds (16%) accounted for 38% of the total variance. The interaction of vertical turbulent diffusion variations with initial source dispersion and time-dependent advection accounted for the remainder (24%) of the explained variance. Specific proposals for model improvement were identified and put forward as recommendations.
2. The model estimates of CO concentrations were found to be insensitive to two possible choices of similarity-theory coefficients, to the use of momentum or heat

diffusion coefficients, and roughness length. However, model estimates were moderately sensitive to emission factors, initial source dispersion parameters, and the heights of measurement of vertical air temperature differences.

3. Model performance was appreciably better than those of three alternative simple box models which do not require meteorological tower data.

Although the test results were encouraging, a large gap remains between explained variance and the total variance of the data. Further model improvement is both possible and desirable if high confidence is to be placed in its use for assessment of physical factors which lead to serious urban air pollution episodes.

5. RECOMMENDATIONS

1. It is recommended that the diffusion model described in this report be verified using CO or other non-reactive motor vehicle exhaust pollutant concentrations from one or more additional cities having urban meteorological towers.
2. It is recommended that additional measurements of initial source dispersion be made in order to evaluate an effective diffusion coefficient and possible variations of such a coefficient with atmospheric stability. Such measurements should be carried out downwind of a single well-defined crosswind line source and should consist of simultaneous vertical profiles of wind speed, temperature, and CO concentrations.
3. It is recommended that serious consideration be given to the possibility of instrumenting a new urban meteorological tower in Edmonton. The tower should be located several kilometers from the city limits. Minimum instrumentation for application to ground-level area source diffusion problems consist of thermometers at 1 or 2 m, a second level between 10 and 20 m, and at the top of the tower, plus a low-threshold ($0.5\ m \cdot s^{-1}$) anemometer at the top of the tower. Hourly mean values of vertical temperature differences, wind speed, and wind direction are required. A tower height of 40 to 50 m appears to be adequate for this application.
4. It is recommended that additional model development be undertaken in order to improve its performance and thereby increase confidence in the assessment of the relative importance of various factors that can cause serious urban air pollution episodes. In particular, there is a need for a new mathematical solution to the diffusion equation and a need for investigation

of the importance of wind direction changes in very light wind speeds. A new mathematical solution is needed to accommodate vertical variations in diffusion coefficient along with non-zero coefficients at ground level.

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